RECEIVED APR 0 3 2003

REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0186

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 10 March 2003	3. REPORT TYPE AND DATES COVERED Final Report 07/15/99 to 12/14/02

4. TITLE AND SUBTITLE
Distributed Modeling and Control of Adaptive Wings

5. FUNDING NUMBERS
F49620-99-1-0294

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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Arlington, VA 22203-1977

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Air Force Office of Scientific Research position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

New generations of highly-maneuverable aircraft, such as Uninhabited Combat Air Vehicles (UCAV) or Micro Air Vehicles (MAV), are likely to feature very flexible lifting surfaces. In order to enhance their stealth properties and maneuverability, the possibility of using smart wings and morphing airfoils instead of conventional, hinged control surfaces is investigated. This task requires a fundamental understanding of the interaction between fluid, structure and control system, in a coded form that is fast enough to design with. This DARPA-funded project takes a fundamental approach to understanding the relevant physical phenomena using different models of a flying wing vehicle in flight. We have developed a model that is consistent with distributed control, and have exercised this model to determine what progress is possible in terms of flight control (lift, drag, and maneuver performance) with morphing wings. For this purpose, different modeling levels are examined and combined with a variety of distributed control approaches to determine exactly what types of maneuvers and flight regimes may be possible, and to determine the forces, moments, and deflections that would be needed from the actuation community in order to fly an aircraft completely without the use of discrete control surfaces.

This year's progress has been to bring together several elements (aerodynamics, flight dynamics, shape generation, and control) to determine bounds on the required forces, moments and strokes for flying by morphing.

14. SUBJECT TERMS morphing unmanned aircraft, active control, aerodynamics	15. NUMBER OF PAGES 6
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20030602 126

Final Report - March 10, 2003
on
Distributed Modeling and Control of Adaptive Wings

(AFOSR Grant No. F49620-99-1-0294)
For the period 07/15/99 to 12/14/02

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1. Abstract
New generations of highly-maneuverable aircraft, such as Uninhabited Combat Air Vehicles (UCAV) or Micro Air Vehicles (MAV) are likely to feature very flexible lifting surfaces. In order to enhance their stealth properties, the possibility of using smart wings and morphing airfoils instead of conventional, hinged control surfaces is currently under investigation. This task requires a fundamental understanding of the interaction between fluid, structure and control system, which is currently not available. This project takes a fundamental approach to understanding the relevant physical phenomena based on using different models of a flying wing vehicle in flight. Our goal is to build a model that is consistent with distributed control and to exercise this model to determine what progress is possible in terms of flight control (lift, drag and maneuver performance) with an adaptive wing. For this purpose, different modeling levels are examined and combined with a variety of distributed control approaches to determine exactly what types of maneuvers and flight regimes may be possible.

2. Objectives
The program goal is the determination of the minimum control energy required to increase the maneuverability and performance of a flapless UCAV using smart structures and morphing airfoil technology. The program objectives are to determine the boundaries of adaptive wing performance by addressing the following issues: (1) Mimic the effects of wings with conventional, discrete control surfaces. This will establish a comparison baseline for the performance evaluation of smart wings with morphing airfoils. (2) Determine the actuation energy, forces, moments, displacements and time constants that are required of smart actuators to achieve the maneuverability and performance of air vehicles with conventional control surfaces, by using morphing wings, i.e., wings which will change their shape but have no control surfaces. Ultimately, this will enable one to determine the control power depending on the maneuverability and/or vehicle performance. (3) Investigate the use of distributed actuation/control devices to: (i) enhance the maneuverability of a highly-flexible wing, and (ii) increase the performance

of the vehicle by expanding its flight envelope and/or its adaptability to different, often contrary, mission requirements (multi-mission vehicle).

3. Accomplishments/New Findings

This project evaluates the performance of a smart wing as compared to a baseline wing with control surfaces. Measurements of the effectiveness of the smart wing can be in terms of required time constants, forces, moments, and control power requirements to obtain maneuverability and performance characteristics similar to or superior to those of a conventional wing. Several models of a generic adaptive wing at different levels of sophistication have been developed, and the behavior of an adaptive wing under various control schemes has been examined.

The *adaptive structures* work focuses on the three-dimensional structural/aeroelastic modeling of a generic flexible UCAV wing/fuselage configuration. The model allows a refined analysis of the wing structure featuring spars, ribs, and skins. It incorporates distributed internal actuation and can be easily adapted to changes in the structural configuration. This model is being used as a planform to study the influence of distributed sensing/actuating and morphing airfoils on flight performance. It is completely validated by finite element analysis.

The *dynamics and control* work studies morphing airfoils in steady and unsteady flow and innovative strategies to control the aircraft using wing morphing. Special attention is given to the three-dimensional interaction of pitch, yaw, and roll control in the absence of vertical control surfaces. A six-degree-of-freedom rigid body flight simulator featuring a vehicle with morphing airfoils has been implemented and validated by finite element simulations.

The *aeroservoelasticity* work investigates aeroelastic effects of structural changes and the possibility of energy transfer between structure and airflow to facilitate structural morphing. One aspect of the aerodynamics work in this task is the drag prediction of morphing airfoils to create yawing moments sufficient to provide yaw control without vertical control surfaces. Using innovative morphing airfoil concepts, the potential of shape changes to create yawing moments in the order of magnitude of vertical control surfaces or split rudders was investigated.

For the morphing wing, a c_L increase equivalent to the one obtained from a flap deflection is being achieved by modification of the airfoil camber and twist using the distributed actuation scheme described above. The wing morphing is calibrated to yield the same c_L increase as the 15° downward deflected flap at reference conditions. We are able to show that omitting hinged control surfaces promises improvements in the aerodynamic quality of the wing. The pressure distribution of the smart wing does not exhibit the suction peak of a hinged flap. Furthermore, the absence of sharp edges and deflected surfaces reduces radar signature and visibility of the vehicle, thus enhancing its stealth properties.

In summary, this program's efforts are highlighted by:

1) Development of a structural and aeroelastic model for a complex morphing wing planform.
2) Validation of the model against a full finite element analysis.
3) Verifying that the model is suitable for computing actuation energy and power requirements for morphing wings.
4) Development of a design tool for a morphing wing structural and distributed actuation optimization.
5) Development of a simulation tool for control system analysis and optimization.
6) Computation of the control energy and power as the wing is morphed for flight control, and comparison of this energy to that required for a conventional, flapped wing.

In general, morphing will require more energy than a flapped wing which does not have to overcome or fight against internal strain energies. However, performance with the morphing wing is higher and the idea of building a wing to morph rather than morphing a wing built for flaps has yet to be pursued. Our goal has been to use these tools to develop a scalable system for morphing wings.

Relationship to Air Force Needs. Several adaptive wing programs are ongoing in Air Force Research Laboratories and by contractors under Air Force support. Clearly, the modern Air Force is likely to use Uninhabited Combat Air Vehicles. Such vehicles, without conventional flaps or vertical control surfaces, would show enhanced stealth properties and reduced radar signature, thus increasing enemy penetration and lethality without putting human pilots at risk. Hence, this research addresses issues which are likely to influence a variety of Air Force programs and enabling technologies by providing insight into the requirements of an adaptive wing.

4. Personnel Supported by and/or Associated with the Research Effort
Faculty: Daniel J. Inman, Harry H. Robertshaw, Bill Mason, Rakesh K. Kapania
Post-docs: none
Students: Greg Pettit, David Neal, Chris Johnston

5. Publications

Gern, Frank H., Kapania, Rakesh K., and Inman, D. J., "Structural and Aeroelastic Modeling of General Platform UCAV Wings with Morphing Airfoils," *AIAA Journal,* Vol. 40, No. 4, April 2002, pp. 628 – 637. (Did not appear until after May 15, 2002).

F. Gern, D. J. Inman, and R. K. Kapania, ``Structural and Aeroelastic Modeling of General Planform UCAV Wings with Morphing Airfoils," 42nd AIAA/ASME/ASCE/ AHS/ASC Structures, Structural Dynamics, and Materials Conference, Seattle, WA, April 2001, Paper No. AIAA-2001-1369, 11 pages.

F. Gern, D. J. Inman, and R. K. Kapania, "Distributed Actuation of Smart Wings with Morphing Airfoil Sections,'' AIAA-2002-1629, 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference," April 2002, Denver, CO, 10 pages. Tentatively accepted for publication in AIAA Journal.

Y. Liu, R. K. Kapania, F. H. Gern, and D. J. Inman, "Equivalent Plate Modeling of Arbitrary Planform Wings," International Conference on Computational Engineering and Sciences, ICES 2000, Los Angeles, CA, August 21-25, 2000. *Advances in Computational Engineering and Sciences,* S. N. Atluri and F. W. Brust eds., pp. 515-521.

Natarajan, Anand, Kapania, Rakesh, K., and Inman, Daniel, J., "Near-Exact Analytical Solutions of Linear Time Variant Systems," 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Seattle, WA, April 2001, Paper No. AIAA-2001-1295, 13 pages.

Natarajan, Anand, Kapania, Rakesh, K., and Inman, Daniel, J., "Near-Exact Analytical Solutions of Linear Time Variant Systems," *AIAA Journal,* Vol. 40, No. 11, pp. 2362-2366.

Natarajan, Anand, Kapania, Rakesh, K., and Inman, Daniel, J., "Aeroelastic Analysis of Adaptive Bumps Used as Drag," *AIAA Journal of Aircraft,* submitted 2001

Natarajan, A., Kapania, R. K. and Inman, D. J., "Aeroelastic Analysis of Adaptable Bumps Used as Drag Rudders", 40th AIAA Aerospace Sciences Meeting and Exhibit, 14-17 Jan. 2002, AIAA paper number 2002-0707.

Natarajan, A., Kapania, R. K. and Inman, D. J., "Aeroelastic Response of Adaptable Airfoils Using Neural Networks", AIAA MDO Conference, Atlanta, GA., Sept. 4- 6, 2002. Revised version submitted for the *AIAA Journal.*

A. Natarajan, R.K. Kapania, and D.J. Inman , ``The Performance of Adaptive Bumps as Drag Rudders. "*AIAA-2002-0707,* 40th AIAA Aerospace Sciences Meeting and Exhibit, Jan 2002, Reno, Nevada, 20 pages. Submitted to *Journal of Aircraft.*

A. Natarajan, R. K. Kapania, and D. J. Inman, ``Aeroelasticity of Morphing Wings Using Neural Networks,'' Report No. VPI-AOE-281, Aerospace and Ocean Engineering, Blacksburg, VA, 24061.

Pettit, G. W., Robertshaw, H. H., and Inman, D. J., 2001, "A Model to Evaluate Energy Requirements of Active Materials in Morphing Wings Including Aerodynamic Forces", 12th International Conference on Adaptive Structures and Technologies, College Park Maryland, October 2001.

D. J. Inman, F. H. Gern, H. H. Robertshaw, R. K. Kapania, G. Pettit, E. Sulaeman, A. Nataraj, and E. Sulaeman, `` Comments on Prospects of Fully Adaptive Aircraft Wings,'' SPIE Paper SS 4332-01, 8th International Symposium on Smart Structures and Materials.

Newport Beach, CA. March 2001.

Inman, D. J., "Applications of Smart Materials in Structures" Tutorial, National Space and Missiles Materials Symposium, June 24-28, 2002, Colorado Springs, CO.

Inman, D. J. and Robertshaw, H. H., "Wings Out of the Box" DARPA CHAP Review, Buffalo, NY, June 19-21, 2002.

Inman, D. J., "Distributed Control of Morphing Aircraft" AFOSR Program Review, Roslynn VA, October 2, 2002.

Inman, D. J., "Ultra Flexible Spacecraft and Morphing UAVs", ICAM Workshop on Control and Identification in Honor of Gene Cliff's Retirement, September 27-28, 2002, Blacksburg, VA.

6. Interactions and Transitions:

a. ***Presentations:*** The following were made by D. J. Inman:

"Applications of Smart Materials in Structures" Tutorial, National Space and Missiles Materials Symposium, June 24-28, 2002, Colorado Springs, CO.

"Wings Out of the Box' DARPA Program Review, June, 19-21, 2002, Buffalo New York.

"Distributed Control of Morphing Aircraft" AFOSR Program Review, Roslynn VA, October 2, 2002.

"A Model to Evaluate Energy Requirements of Active Materials in Morphing Wings Including Aerodynamic Forces", 12th International Conference on Adaptive Structures and Technologies, College Park Maryland, October 2001.

Wings Out of the Box: Morphing", DARPA TIM, November 2001, Wright Patterson Air Force Base.

"Ultra Flexible Spacecraft and Morphing UAVs", ICAM Workshop on Control and Identification in Honor of Gene Cliff's Retirement, September 27-28, 2002, Blacksburg, VA.

Consultation and Advisory:
Prof. Inman is currently serving a five-year term on the Division Review Committee and the Weapons Engineering and Manufacturing Review Committee for Los Alamos National Laboratories.

b. **Transitions**

Prof. Inman interacted on several occasions with Dr. Brian Sanders of the AFRL's Multifunctional Adaptive Structures Team (WPAFB). Professor Inman spent one week visiting the team during the summer of 2002, and two members of the AFRL team visited Virginia Tech to advise and collaborate with the VT Morphing Wing Team funded by this proposal.

7. Patents

None

8. Honors and Awards

D. J. Inman became a Fellow of AIAA.